

# **TIDAL VARIATION IN TURBULENT EDDY SIZES IN AN ESTUARY**

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## **ABSTRACT**

Density microstructure measurements made in a tidal channel in South San Francisco Bay showed that the vertical length scale of turbulent eddies was proportional to current speed during spring tide but was largest during the flood at neap tide, and varied up to five-fold over a tidal cycle. The data were collected using a free-falling fast-response CTD at two locations and over three tidal cycles. Turbulent overturning eddies were identified from the vertical distribution of Thorpe displacements, and their vertical length scale obtained from the mean Thorpe scale over the depth interval of the eddy. Minimum eddy sizes occurred at, or just after, slack water. The largest eddies were observed during maximum to late flood when the vertical stratification was least. The observed variation in eddy sizes is expected to produce an intra-tidal variation in  $\epsilon$ , the turbulent kinetic energy dissipation rate, and  $K_p$ , the vertical eddy diffusivity, of at least two orders of magnitude.

## **INTRODUCTION**

Estimates of mixing rates in estuarine waters are dependent upon knowledge of the length and time scales associated with small-scale turbulent diffusion. In recent years increased understanding of the turbulent processes in tidal flows has resulted from several investigations into their structure and spectral representation. The earliest studies showed that Reynolds stress generated at the bed is highly intermittent (Heathershaw 1974, 1979; Gordon and Witting 1977; Heathershaw and Simpson 1978), and spectral plots of measured turbulent velocity exhibit an inertial subrange (Grant et al. 1962; Gargett et al. 1984; Gross and Nowell 1985; West and Shiono 1985) suggesting that estuarine turbulence follows the Kolmogorov universal spectrum. More recent studies have utilized acoustic current meters (Gargett and Moum 1995; Stacey et al. 1999; Trowbridge et al. 1999) or free-falling microstructure profilers (Simpson et al. 1996; Peters 1997, 1999, 2003; Peters and Bokhorst 2000, 2001; Rippeth et al. 2001; Etemad-Shahidi and Imberger 2002). The results of these investigations have shown that the rate of turbulent kinetic energy dissipation ( $\epsilon$ ) in estuarine tidal flows is larger than in the open ocean. Measured values of  $\epsilon$  range from  $10^{-7}$  to  $10^{-4}$  W kg<sup>-1</sup>; the values can vary by a factor of 100 over a tidal cycle (Simpson et al. 1996; Peters 1999). The largest values generally occur nearest the bed (Peters 1999; Peters and Bokhorst 2000). Water column stratification does influence both shear production and dissipation. Where the water column is stratified throughout the tidal cycle,  $\epsilon$  values below the pycnocline vary directly with the magnitude of the tidal current and are significantly weaker in or above the pycnocline (Simpson et al. 1996). If the water column periodically de-stratifies due to tidal

Report Documentation Page			Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>2005</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-2005 to 00-00-2005</b>		
4. TITLE AND SUBTITLE <b>Tidal Variation in Turbulent Eddy Sizes in an Estuary</b>		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)	5d. PROJECT NUMBER			
	5e. TASK NUMBER			
	5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. Coast Guard Academy ,Department of Science,31 Mohegan Avenue ,New London ,CT,06320-8103</b>		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT <b>Density microstructure measurements made in a tidal channel in South San Francisco Bay showed that the vertical length scale of turbulent eddies was proportional to current speed during spring tide but was largest during the flood at neap tide, and varied up to five-fold over a tidal cycle. The data were collected using a free-falling fast-response CTD at two locations and over three tidal cycles. Turbulent overturning eddies were identified from the vertical distribution of Thorpe displacements, and their vertical length scale obtained from the mean Thorpe scale over the depth interval of the eddy. Minimum eddy sizes occurred at, or just after, slack water. The largest eddies were observed during maximum to late flood when the vertical stratification was least. The observed variation in eddy sizes is expected to produce an intra-tidal variation in <math>\epsilon</math>, the turbulent kinetic energy dissipation rate, and <math>K</math>, the vertical eddy diffusivity, of at least two orders of magnitude.</b>				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>12</b>
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>		

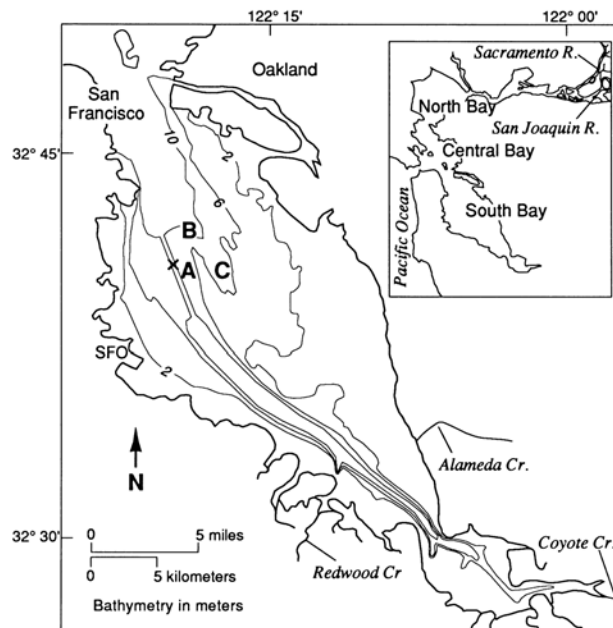
straining, maximum  $\varepsilon$  values may extend to the surface during flood current (Rippeth et al. 2001). Similarly, over the neap-spring cycle, Peters (1999) found that  $\varepsilon$  at mid-depth varied quarter-diurnally at spring tides when stratification was weaker, but semi-diurnally at neap tides.

The length scale of the turbulent overturning eddies can be estimated using the Thorpe scale (Thorpe 1977; Dillon 1982). Peters (1997) observed Thorpe scales in the Hudson River as large as 1 m in the lower layer on neap tides, and throughout the water column on spring tides. He also found that the Thorpe scale was highly correlated with the Ozmidov scale, a length scale calculated using the viscous dissipation rate and the buoyancy frequency, except in the sections of the water column with very small values of  $N^2$ , which were typically closest to the bed. Stacey et al. (1999), in their study in northern San Francisco Bay, also calculated a stratification length scale, equivalent to the Ozmidov scale but using shear production values rather than dissipation, and found similar magnitudes and dependence on water column stratification. Both these studies were done in estuaries with moderate to large stratification. In this paper we present results of a study that utilized a free-falling microstructure profiling CTD to measure the Thorpe scale and turbulent eddy size in a weakly stratified estuary, South San Francisco Bay. The measurements were obtained at two locations and over several tidal cycles, and show a clear scaling of eddy size with current speed at spring tide, but a semi-diurnal variation of eddy size at neap tide, with the largest eddies during the flood.

## METHODS

The data were collected at three locations in South San Francisco Bay, a broad coastal plain estuary containing one main tidal channel bordered by extensive shoals (Figure 1). Minimal freshwater inflow and moderate tidal currents of up to  $1 \text{ m s}^{-1}$  combine to make this estuary generally weakly-stratified, although the channel reaches may become more strongly stratified during neap tides, especially during the winter-spring wet season (Walters et al. 1985). The stations were located in the main channel (A, depth = 8 m, see Fig. 1), over the adjacent shoals (B, depth = 6 m), and in a secondary channel to the east (C, depth = 8 m). The sampling was repeated throughout a tidal cycle on three occasions: 30 March 1988, 8 April 1988, both neap tides, and 19 April 1988, a spring tide.

At each station vertical profiles of density microstructure were obtained using a free-falling Ocean Sensors Inc. CTD (Model 100) which sampled at 175 Hz and was adjusted to fall at approximately  $0.8 \text{ m s}^{-1}$ . This instrument is fitted with an FP07 (Fenwal Inc.) thermistor and a 4-electrode conductivity cell (Head 1983). Data collection began and ended at specified depths (pressures) and the profiling continued until the memory was full. The instrument was then retrieved; the data uploaded to an onboard PC and another data collection cycle begun. Additional data was obtained with a Seabird 9/11 CTD sampling at 24 Hz. An Endeco 174 current meter was moored 2.1 m below MLLW near station A, and an Endeco 1032 water level recorder was moored near station C.



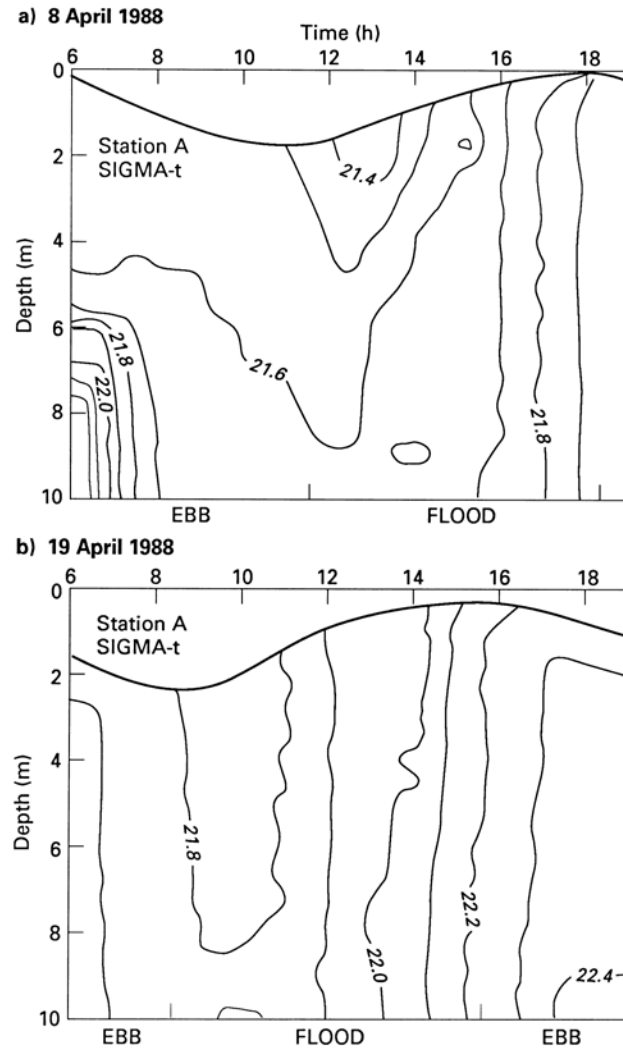
**Figure 1** Location of sampling stations in South San Francisco Bay. Density measurements were made at A, B and C; a current meter (x) was located near A, and a water level recorder positioned near C.

On the first cruise, 30 March 1988, the three stations were sampled in turn, once an hour for 13 hours. At each station three profiles, 30 seconds apart were obtained with the rapid sampling OS CTD, and one profile collected with the Seabird CTD. On subsequent cruises (8,19 April 1988) the sampling alternated between a circuit of all three stations, and two periods of intensive sampling, a half-hour apart, at station A. The intensive sampling consisted of ten profiles with the OS CTD and one profile with the SBE CTD. During the initial data processing salinity and density were calculated from the CTD records, the current meter data was vector averaged into half-hourly intervals, and the water level data averaged over hourly intervals. Only data from stations A and C will be presented in this paper.

## RESULTS

The estuary remained only weakly stratified during the spring in 1988. This was a result of very low flows into San Francisco Bay from the San Joaquin and Sacramento Rivers during that year, and is in contrast to other spring periods when river flows are high and stratification can be strong (Walters et al. 1985, Huzzey et al. 1989). Figure 2 shows the density at station A as a function of depth and time for the measurement period on April 8, a neap tide, and April 19, a spring tide. The maximum vertical density difference observed on all three sampling days was  $0.65 \sigma_t$  during the early ebb tide on 8 April (Fig. 2a). On this date the stratification decreased during the latter part of the ebb and early flood tide, the water column becoming very well-mixed by the end of the flood tide. On April 19 (Fig. 2b) the least stratification was observed during the mid to late flood tide when the vertical density differences were less than  $0.1 \sigma_t$ . A similar change in

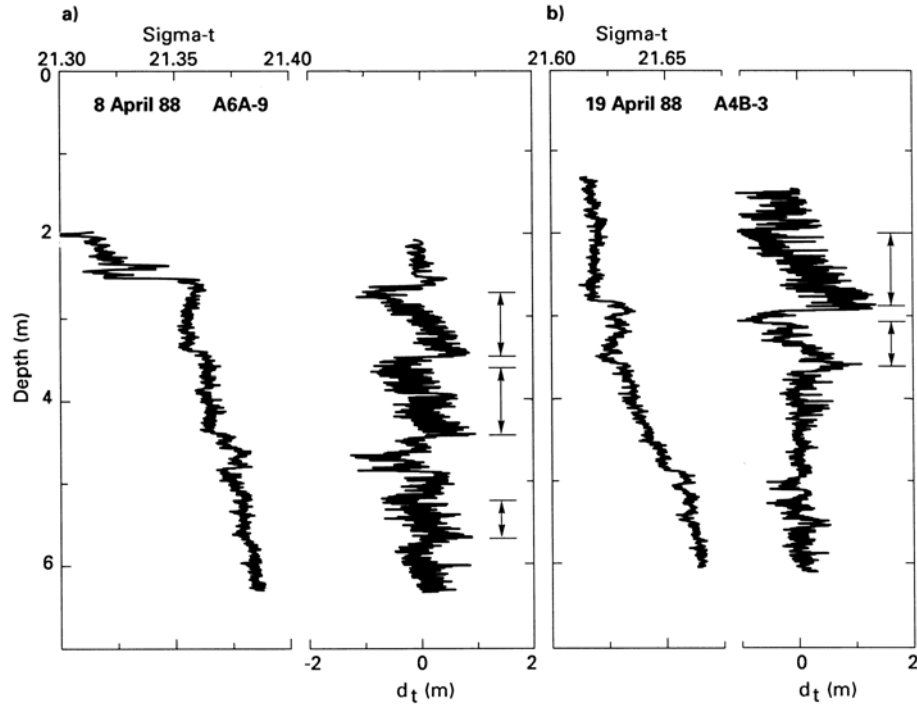
stratification through the tidal cycle has been observed in other partially stratified estuaries (e.g. Huzzey 1988) and can be attributed to tidal straining (Simpson et al. 1990).



**Figure 2** Vertical density distribution between 0600 and 1900 hours local time at station A on (a) 8 April 1988, and (b) 19 April 1988. Data were collected by the Seabird CTD.

A method for estimating a length scale for turbulent overturning events was developed by Thorpe (1977), and consists of rearranging, or re-ordering, an instantaneous vertical density profile into one that is statically stable. The vertical distance each parcel of water has to be moved to obtain the new profile is termed the Thorpe displacement,  $d_t$ . The Thorpe scale  $L_t$  is defined as the root mean square Thorpe displacement, i.e.,  $L_t = \langle d_t^2 \rangle^{0.5}$  (Dillon 1982), and is proportional to the mean eddy size, assuming that the mean horizontal density gradient is much smaller than the vertical gradient. Data collected by the OS CTD were used to obtain the Thorpe displacements and associated Thorpe scales. Figure 3 shows two examples of vertical density profiles and the associated vertical distribution of the Thorpe displacements. The fine-scale density differences observed were above the noise level of the OS CTD. The re-ordering was done using a bubble-sort

algorithm. An overturning eddy is characterized by a pattern of large negative Thorpe displacements followed by increasingly positive displacements forming a "backwards-Z" pattern. Often the upper and lower boundaries are quite sharp (Dillon 1982). The profile in Figure 3a was obtained near slack water on April 8. Three eddies can be identified centered around depths of 3 m, 4 m and 5.5 m.

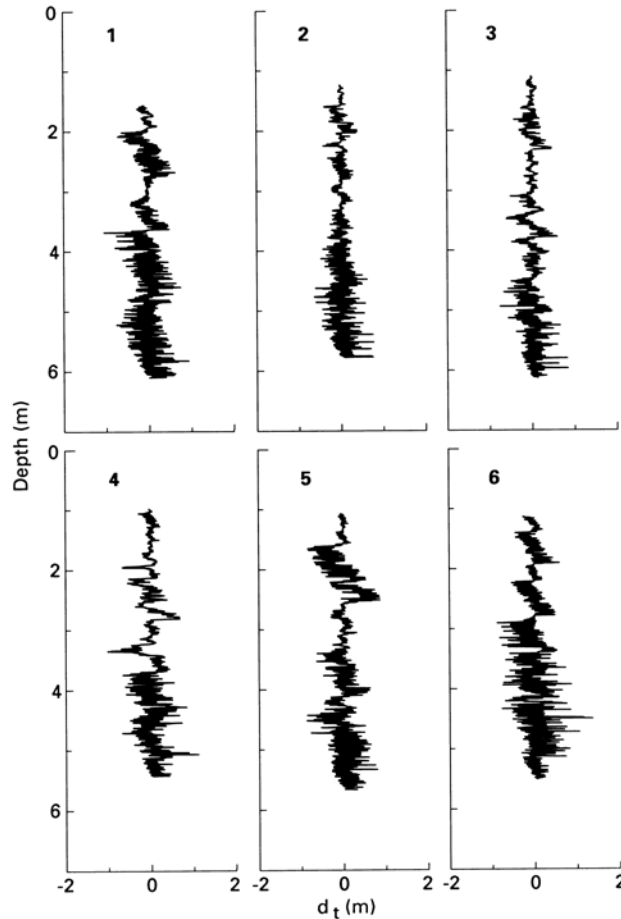


**Figure 3** Two examples of vertical density ( $\sigma_t$ ) profiles at station A obtained using the OS CTD (on the left of each box), and the vertical distribution of Thorpe displacements (on the right of each box). Overturning eddies are marked by the vertical bars. (a) cast A6A-9, 8 April 1988, 1107 local time (b) cast A4B-3, 19 April 1988, 0933 local time

Throughout this study the Thorpe scale was calculated from the Thorpe displacements in 0.3 m depth increments, and the appropriate values of the Thorpe scale then averaged over the depth interval of the eddy to obtain the mean Thorpe scale for the eddy,  $L_e$ ; that is,  $L_e = \langle L_t \rangle_{\text{eddy}}$ . The mean Thorpe scales for the eddies in Figure 3a were 0.42 m, 0.37 m and 0.33 m respectively. The profile in Figure 3b was recorded during late ebb on April 19 and shows two eddies of greater vertical extent between 2 m and 3.5 m, which had mean Thorpe scales of 0.59 m and 0.42 m. The Thorpe displacements were obtained for all the microstructure density profiles at stations A and C, a total of 328 casts. The CTD sampled from a depth of 0.5 m below the surface to 0.3 m above the bed, but only the data from 2 m to 0.5 m above the bed were used in this study. Eddies or overturning structures were identified as illustrated in Figure 3, and the mean Thorpe scale, or length scale,  $L_e$ , for these eddies was calculated.

The time scale associated with the overturning eddies in this tidal flow was found to be very short. Figure 4 shows the vertical distribution of Thorpe displacements from a sequence of casts

taken 30 seconds apart near maximum flood on 8 April. The pattern of Thorpe displacements, and the position and vertical extent of any eddies, differed greatly from one cast to the next. For example in cast 5 there were three eddies, none of which were evident in cast 6; in cast 7 two eddies could be seen at mid-depth which did not persist to cast 8, and similarly rapid changes were seen in the upper 3.5 m between casts 9 and 10. The disappearance of eddies between samples may be partially attributed to advection. However, such variability was characteristic of all sampling on all days, regardless of the tidal phase, and whether or not the boat was drifting with the tidal current. This suggests that the characteristic time scale of growth or decay of these eddies is less than 30 seconds, the time between successive casts.



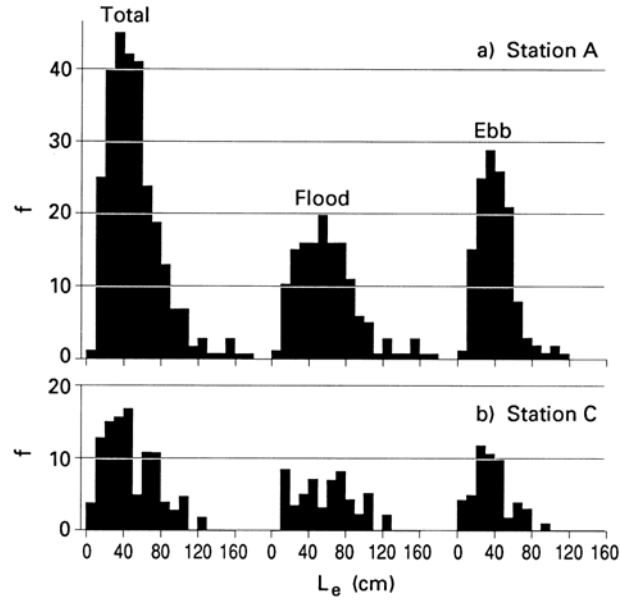
**Figure 4** The vertical distribution of Thorpe displacements from a sequence of six casts taken at station A between 1315 and 1318 local time on 8 April 1988.

The mean and range of observed eddy sizes for each station and sampling date is listed in Table 1. There was no significant difference (at the 95% confidence level) in the mean eddy size between stations, or between cruises, with the exception of station A on March 30 and April 8. Note however that the range of observed eddy sizes was of such an extent that for every cruise the maximum values of  $L_e$  were 4 to 5 times the minimum values. For each station the observations from all three cruises were combined and plotted as frequency distributions (Figure 5). For both stations  $L_e$  was not normally distributed (Kolmogorov-Smirnov test, Sokal and Rohlf 1981). The

distribution at station A is skewed to the right while that of station C is approximately bimodal. Separating the observed values of  $L_e$  according to the tidal phase shows that at station A both the flood and ebb values are also skewed to the right (see Fig. 5) although the flood values have a broader range. At station C the differences between the flood and ebb frequency distributions are greater than those from A.

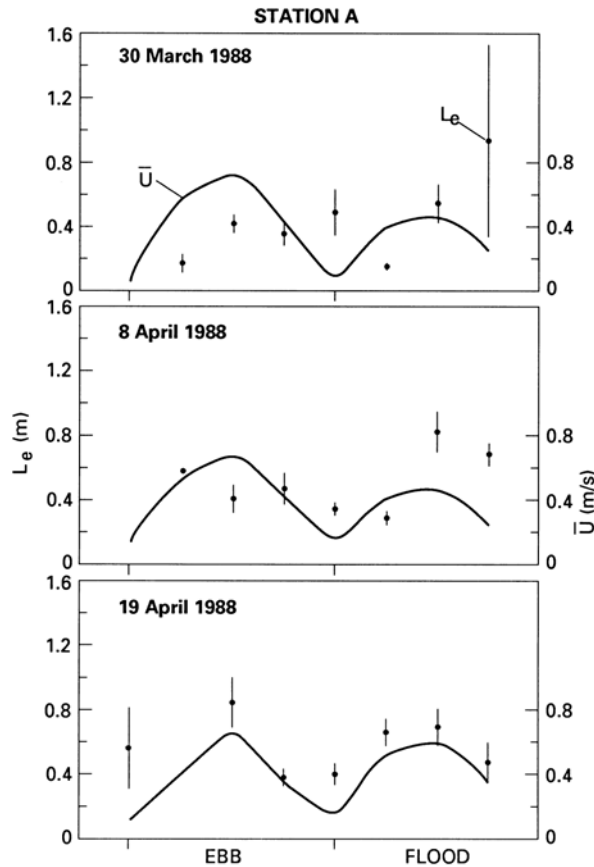
Date	Station	mean $L_e$ (m)	range of $L_e$ (m)
30 March	A	0.41	0.16 – 0.94
	C	0.50	0.05 – 1.29
8 April	A	0.57	0.28 – 1.05
	C	0.52	0.12 – 0.97
19 April	A	0.59	0.30 – 1.36
	C	0.49	0.15 – 1.23

**Table 1** The mean and range of the vertical length scales ( $L_e$ ) of the overturning eddies observed at stations A and C for the three sampling dates.

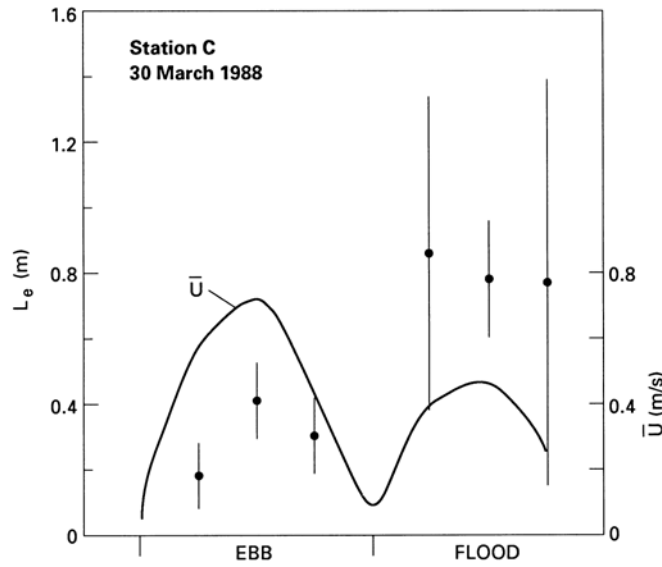


**Figure 5** Frequency distributions of the length,  $L_e$ , of observed eddies. Each panel shows a histogram for the total number of eddies observed at that station. The distributions for those observations which occurred during the flood and ebb portions of the tidal cycle (i.e. between the observed or predicted times of SBE and SBF) are also shown. (a) station A (b) station C

One of the questions addressed in this study was the intra-tidal variation in turbulent mixing. The variation of eddy size with time was examined by dividing the tidal cycle into 8 segments: slack-before-ebb (SBE), early, maximum and late ebb, slack-before-flood (SBF), early, maximum and late flood. For each of these intervals a mean velocity was calculated using the observed currents near station A (see Fig. 1) for March 30 and April 8, and predicted currents from historical data sets (Cheng and Gartner 1984) for April 19. The mean value of  $L_e$  in each of these tidal segments was also calculated, and is plotted in Figures 6 and 7, together with the tidal current speeds to show the tidal-time variation in  $L_e$ . For both of the neap tide sampling days (30 March and 8 April) mean  $L_e$  was largest during late flood at Station A and throughout the flood at Station C. This change in the mean eddy size does not correspond directly to tidal current speed, as the ebb currents on these days were stronger than the flood currents. The minimum values of  $L_e$  occurred at early ebb and early flood on March 30, and early flood on April 8. On April 19, a spring tide, at station A the mean value of  $L_e$  was slightly larger during the ebb tide and the change in  $L_e$  appeared to be closely in phase with the speed of the tidal currents, i.e. have a quarter-diurnal periodicity (Fig. 6c). Station C was sampled too infrequently on April 8 and 19 to determine temporal trends. The 95% confidence intervals in Figures 6 and 7 represent the variation in eddy size; this variation was largest during the flood phase of the neap tide sampling days.



**Figure 6** Variation in  $L_e$  through the tidal cycle at station A. The solid line represents current speed averaged over 1.5 hour increments. The error bars indicate the 95% confidence limits on  $L_e$ . (a) 30 March 1988 (b) 8 April 1988 (c) 19 April 1988



**Figure 7** Variation in  $L_e$  through the tidal cycle at station C. The solid line represents current speed in the main channel averaged over 1.5 hour increments. The error bars indicate the 95% confidence limits on  $L_e$ .

Although the size of the eddies varied with the tidal cycle, the percentage of the water column containing distinct turbulent overturns, calculated as the sum of the eddy depths divided by the total depth sampled, did not vary tidally. The mean value was approximately 10%, but these measurements do not include the upper 2 m or the lowest 0.5 m of the water column. At any given time throughout the tidal cycle the range was large (from 0 up to as much as 38%) because, as is evident in Figure 4, successive casts may show either zero eddies or several eddies.

## DISCUSSION

The mean size of overturning eddies in South San Francisco Bay tidal channels was 0.51 m but varied by as much as 1.24 m over a tidal cycle. In the open ocean Dillon (1982) found that the Thorpe scale is highly correlated with the Ozmidov scale,  $L_o = [\varepsilon/N^3]^{1/2}$ , such that  $L_o \approx 0.8 L_t$ . For the Hudson River, Peters (1997) found that  $L_o \approx 1.5 L_t$  except very near the bed. As the data collected in South San Francisco Bay were collected at heights of greater than 0.5 m above the bed, and all identified eddies were centered at least 2 m above the bed, it is assumed that a direct correlation between  $L_o$  and  $L_t$  also applies to South San Francisco Bay. It follows therefore that the magnitude of  $L_e$ , and its change through the tidal cycle, should reflect the magnitude and changes in either  $\varepsilon$  or  $N$ . During spring tide (April 19) at Station A the maximum eddy sizes were observed at maximum currents; this result is consistent with previous studies which have shown that  $\varepsilon$  varies with tidal current speed (e.g. Simpson et al. 1996; Peters and Bokhorst 2000) and suggests that eddy sizes on this date were controlled by changes in  $\varepsilon$ . Between maximum ebb and late ebb there was a difference in  $L_e$  of at least 25 cm (see Fig. 6). Assuming a constant value of  $N$ , if  $\varepsilon$  is proportional to  $(L_e)^2$  then this implies that values of  $\varepsilon$  in South San Francisco Bay varied by as

much as  $10^2$  to  $10^3$  over the tide cycle. This range is slightly higher than the direct measurement of  $\epsilon$  by Peters (1999) and Rippeth et al. (2001) who both found tidal cycle variations on the order of  $10^2$ . During neap tides the largest  $L_e$  occurred during flood tides, which were also the times of least stratification (see Fig. 2). Again this result is consistent with other studies in tidal environments, which have found that when the water column is stratified  $\epsilon$  varies more semi-diurnally than quarter-diurnally, with maximum values occurring when stratification is minimum.

Although the rate of turbulent dissipation was not directly measured in this study, the observed eddy sizes can be used to estimate the possibly magnitude and range of  $\epsilon$  in South San Francisco Bay. On dimensional grounds we expect that  $\epsilon$  is proportional to  $L_e^2/t_s^3$ , where  $t_s$  is a time scale in seconds. To evaluate this, we need an appropriate value for  $t_s$ . The average value of  $N$  for the study period was approximately  $0.02 \text{ s}^{-1}$  which gives a time scale of 50 seconds. This time scale is consistent with our observations that eddies either grow or decay in approximately 30 seconds, the time between successive casts. Using the relationship above and the results in Table 1, we find that at Station A,  $\epsilon$  has an estimated mean value of  $2.2 \times 10^{-6} \text{ m}^2 \text{ s}^{-3}$ , and a range of  $1.5 \times 10^{-5}$  to  $2.0 \times 10^{-7} \text{ m}^2 \text{ s}^{-3}$ . These values are very similar to previously reported directly measured values for tidal environments and illustrate that valid estimates of  $\epsilon$  can be made based on fine scale density measurements.

Our observations of  $L_e$  and its range over the tidal cycle imply a corresponding intra-tidal change in vertical eddy diffusivity,  $K_p$ . This coefficient scales according to  $\text{length}^2/\text{time}$ ; using the mean value of  $L_e = 0.51 \text{ m}$  and  $t_s = 50$  seconds, then  $K_p$  will be approximately  $5.2 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ , and over the tidal cycle should vary by a factor of  $10^3$ . For the Hudson River Peters (1999) found that  $K_p$  varied with depth and time between  $10^{-5}$  and  $10^{-2} \text{ m}^2 \text{ s}^{-1}$ , and in northern San Francisco Bay (Suisun Bay), Stacey et al. (1999) found that  $K_p$  varied between  $10^{-4}$  and  $10^{-2} \text{ m}^2 \text{ s}^{-1}$ . Again, our results are similar to observations in more stratified estuaries, and extend the applicability of these turbulent scale relationships to weakly stratified estuaries.

## CONCLUSIONS

The density microstructure measurements made in South San Francisco Bay have clearly shown that the Thorpe (1977) method of estimating the length scale of turbulent overturning events can be applied to estuarine measurements.

The turbulent eddies identified in this way had a very short time scale, evolving or decaying in less than 30 seconds. At spring tides, the magnitude of the eddies was proportional to the tidal current speed and varied by a factor of up to 4 within a tidal cycle. Maximum values occurred at maximum currents, minimum values up to one hour after slack tide. The largest eddies were observed on a neap tide during maximum to late flood when the vertical stratification was least. We speculate that our results correspond to values for  $\epsilon$  of the order of  $10^{-6} \text{ m}^2 \text{ s}^{-3}$  (range:  $10^{-5} - 10^{-7} \text{ m}^2 \text{ s}^{-3}$ ), similar to previously reported values for more stratified estuaries. Furthermore, the observed variation in eddy sizes is expected to produce an intra-tidal variation in  $\epsilon$  and  $K_p$  of at least two orders of magnitude.

## Acknowledgements

We thank D. Codiga and J. Dairiki for programming and field assistance, and J. Bennett, J. Cloern and J. Thompson for field assistance. The current meter deployments were organized and executed by J. Gartner. We also thank the crew of the R/V Polaris, B. Richards, S. Conard and B. LaFleur for their patience and cooperation throughout the cruises. This work was partially supported by N.S.F. grants OCE 86-13749-01 and OCE 87-17678 (T.P., principal investigator). T.P. thanks W.T. Edmondson and S. Emerson of the Univ. of Washington for their hospitality during the initial writing of this paper.

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